FAST ACQUISITION OF OTOACOUSTIC EMISSIONS BY MEANS OF PRINCIPAL COMPONENT ANALYSIS

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Abstract - Transient-Evoked Otoacoustic Emissions (TEOAE) are nonstationary acoustic signals coming from the inner ear after acoustic stimulation by clicks and they are applied as tools in newborn hearing screening programs to allow the early identification of hearing loss and the consequent diagnosis and intervention. In any screening program, the duration of each test is a crucial parameter. For TEOAE, it is strongly influenced by the acquisition procedure, typically based on classical synchronous averaging technique over 260 sweeps, with an average acquisition time of about 2-3 minutes. This paper present an application of Principal Component Analysis (PCA) to rapidly-acquired TEOAE (averaged over only 10, 60 or 100 sweeps) for the detection of this type of cochlear response. The PCA approach is shown to be able to enhance the signal-to-noise ratio (SNR) and, in turn, to allow a correct detection of the responses. Results of the application of this approach in comparison with responses recorded, from the same ears, with classical technique will be shown. The reduction of the acquisition time to about one forth with respect to its typical value and with approximately the same final signal-to-noise ratio will be discussed.

Keywords **- Principal Component Analysis; Fast Acquisition; Otoacoustic Emissions**

I. INTRODUCTION

Transient-Evoked Otoacoustic Emissions (TEOAE) are nonstationary acoustic signals coming from the cochlea in response to short transient stimuli, such as clicks and tone-bursts [1]. These responses can be recorded from the ear canal of all normal adults, children and neonates, and are increasingly used as a clinical test to assess the integrity of the peripheral organ [2]. In particular in newborns, TEOAE can be recorded from all normal ears shortly after birth, and, for this reason, newborn hearing screening protocols based on the measure of TEOAE are now largely implemented [3].

TEOAE are known to be characterized by an extremely high inter-subject variability and intra-subject repeatability. In particular, the inter-subject variability makes the identification of the true emission a crucial task when otoacoustic emissions are utilized in hearing screening programs. Their identification is commonly performed with the help of some simple statistical measure such as the correlation between replicate trials, and, partially, by visual inspection [4]. The rapid diffusion of TEOAE-based hearing screening programs has increased the importance of the search of any method capable of increasing the objectivity and sensitivity of emission identification. In particular, the human eye more readily detects the presence or absence of an otoacoustic emission when it simultaneously sees more than one response collected at different stimulus levels, comparing some mutual features within a set of traces. In clinical practice, this procedure has not yet found widespread acceptance due to the long acquisition time needed for the synchronous averaging technique.

This paper aims to present a method, based on a Principal Component Analysis (PCA) approach, to increase the signal-to-noise ratio (SNR) in a set of click-evoked otoacoustic emissions recorded averaging only a few sweeps. The main goal is that of reducing the acquisition time with respect to the classical procedure typically based on synchronous averaging of a larger number of sweeps.

II. METHODOLOGY

The PCA Approach

Principal component analysis (PCA) involves a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called *principal components*. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. PCA is a well-established tool in the interpretation of analytical data. It depicts separate and close observations from a small-uncorrelated variable set.

When the data is constituted by a set of waveforms, the analysis of the relations between the waveforms in the set could be performed to determine some common characteristics. To this purpose, one should describe them with a minimum number of parameters. One typical approach is based on the linear representation of the set. The general form of a linear representation of a set of *N* data waveforms *s* (t) where *n* ranges from 1 to *N*, is given by:

$$s_n(t) = \sum_{m=1}^{M} c_{nm}\, f_m(t) \qquad (1)$$

where $f_m(t)$ is the m_{th}-basic waveform and c_{nm} is the weighting coefficient, which represents the contribution of the m_{th}-basic waveform to the n_{th}-data waveform. Each data-waveform can be computed by the knowledge of the M basic waveforms and M weighting coefficients. The M basic waveforms with the weighting coefficients can be estimated using the PCA approach [5].

Let us consider the matrices S [N rows x T columns] of the *s*(t) data waveforms, C [N x M] of the weighting coefficients and F [M x T] of the basic waveforms. Thus, relation (1) can be written as:

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Abstract

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$$S = CF \tag{2}$$

The basic waveforms F are typically constrained to be an orthonormal set. Considering now the correlation matrix *R* computed on the data waveforms S, the corresponding eigenvalue diagonal matrix, ë, and the associate eigenvector matrix U, one could easily demonstrate [5] that:

$$C = U\sqrt{l} \tag{3}$$

$$F = \sqrt{1/l}\,U'S \tag{4}$$

where *U'* is the transpose of matrix U.

Now one should consider that a commonly used measure of the size of a signal waveform is its power P_n. Considering Eq. (1) and using the orthogonality relation for the basic waveforms, one should find:

$$P_n = \sum_{m=1}^{M} c_{nt}^2 \tag{5}$$

A measure of the importance of a basic waveform is the power it contributes to the total power of the entire set of waveforms. This contribution, considering also Eq. (3), can be denoted by

$$P_m = \sum_{n=1}^{N} c_{nt}^2 = \sum_{n=1}^{N} l_m u_{nm} = l_m \tag{6}$$

The purpose of developing the theory of linear expansions is that it permits finding expansions that hopefully will perfectly reconstruct *S* utilizing significantly fewer basic waveforms *F*. From Eq. (6) one can easily infer that the eigenvalue $ë_m$ represents the contribution of the *m*th basic waveform to the total power in the set of data waveforms. It then becomes obvious that the most important basic waveforms to use in representing the experimental waveforms are those corresponding to the largest eigenvalues. Thus the eigenvalues can be used to infer the dimensionality of the signal space.

The PCA Approach For Fast Acquisition of TEOAE

The PCA approach described above is applied here to the fast acquisition of a set of TEOAE recorded from the same ear, during the same test session at different stimulus levels. On a practical ground a set of otoacoustic emissions, which were acquired at different stimulus intensity levels is considered as matrix *S*. Each set was composed by 11 responses from the same ear at decreasing stimulus levels (see below) and compiled into a 2D-array resulting in a matrix of 11 rows and 512 columns (see the examples in Fig. 1). Responses to different stimulus intensities were arranged in rows and the post-stimulus time changes in columns.

Following Eq. (1), the set of otoacoustic emissions *S* can be considered as the result of the product between a matrix *F* of basic waveforms and a matrix *C* of weighted coefficients. Hence, considering, as stated before, that the highest eigenvalues are responsible of the most of the power of the responses and, on the contrary, the lowest eigenvalues can be related to noise, one could set at zero the latter ones, sieving the basic waveforms responsible for the actual otoacoustic response from other components due to noise. A set of signals can be reconstructed, constituted by the original set of emissions *S* without the contribution of noise components, hence increasing the SNR.

In order to evaluate the performances of the PCA approach as a whole and identify the optimal setting of the parameters, the *Similitude* was used, defined as the value of the correlation function at zero-lag between a reference set (in the following Golden Standard (GS)) and each rapidly-acquired set, before and after PCA approach. The reference set comprises the responses recorded from the same ear by means of the classical averaging procedure (average over 260 sweeps). *Similitude* was computed in a time window from 6 to 18 ms.

TEOAE Response Acquisition

TEOAE were collected from 15 normal ears of 9 adults with an ILO88 apparatus (Otodynamics Ltd.), with standard adult ILO probes. The recordings were processed on-line with the ILO88 default procedure (sample frequency 25000 samples/s, resulting in 512 sampled points, windowing from 2.5 to 20 ms). TEOAE were recorded using the derived nonlinear mode for acoustic artifact reduction [6]. Clicks were used as stimuli with intensity ranging from 53 to 83 dB SPL, step of 3 dB, for a total number of 11 recordings per ear. For each response, two replicate recordings (A and B) were collected at the same recording conditions. For each test session, four types of responses were recorded: one reference set (Golden Standard GS), consisting of an average of 260 sweeps (typical in clinical practice) and three different rapidly-acquired set of responses, averaged over 10, 60 and 100 sweeps, respectively. All responses were collected during one single recording session, and if possible, without removing the probe from the ear canal, to maintain almost the same recording conditions.

The applied protocol could be summarized as follows:

1. Recording of the four set of 11 TEAOE responses from the same ear at decreasing stimulus levels.
2. Computation of the correlation matrix of *S*. The correlation matrix was computed by the cross covariance between the n_{th} and the k_{th} waveforms, in order to reflect differences in signal intensity.
3. Computation of the corresponding eigenvalue diagonal matrix, ë, and the associate eigenvector matrix *U*.
4. Zeroing all the eigenvalues but the highest two.
5. Computation of *C* and *F* by Eq. (3) and Eq. (4), to obtain , estimation of *S*.
6. Comparison of with the GS set and measuring the performances of the PCA approach by the *Similitude*.

III. Results

Fig. 1 shows an example (Ear #9 - left) of a rapidly acquired set of TEOAE responses (averaged over 60 sweeps) to stimuli at intensities from 53 to 83 dB SPL before (on the left) and after (on the right) the application of the PCA approach.

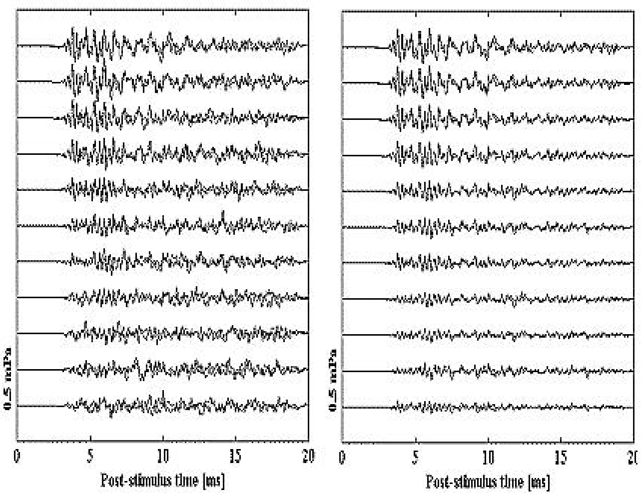

Fig. 1. An example of a set of TEOAE (Ear #9, responses averaged over 60 sweeps) before (on the left) and after (on the right) PCA processing. The responses were recorded t different stimulus intensities, from 53 (bottom trace) to 83 dB SPL (top trace). For each trace, A and B replicates are shown superimposed.

Fig. 2 shows the average *Similitude* for all 15 recordings over stimulus intensity computed for all three rapidly-acquired set of recordings (10, 60 and 100 sweeps). The average *Similitude* for the 60-sweep and 100 sweep set ranges from 49% at the lowest to 90% at the highest stimulus levels, whereas the 10 sweep set, with a very low signal-to-noise ratio before PCA processing, shows figures ranging from 5% to 53% at the lowest and highest stimulus intensities respectively.

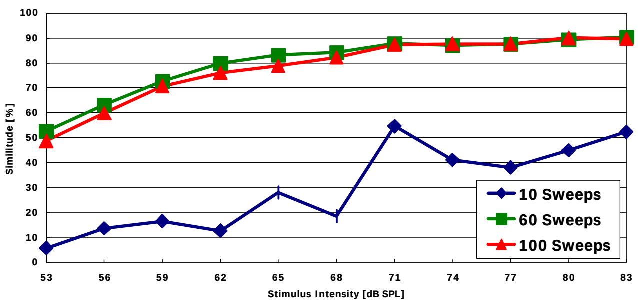

Fig. 2. Similitude as a function of the stimulus intensity of the rapidly acquired set of responses averaged over 10, 60 and 100 sweeps with respect to the GS set. The figures are relative to the average over all ears.

The minimum dimension of each set, i.e., the minimum number of TEOAE responses that should be collected in order to obtain a satisfactory application of PCA, is a crucial parameter for the practical application of the procedure. Also in this case, the *Similitude* between the GS and the rapidly acquired set of signals was observed. PCA was applied to three reduced set of three, four and five responses (from 71 to 83 dB SPL) collected from each ear. The average *Similitude* is shown in Fig. 3. In any case, the maximum difference of the *Similitude* is of 6 PP whereas, at the highest stimuli, the Similitude reaches approximately the 90% and there is practically no difference in applying PCA over a set of 3, 4 or 5 signals.

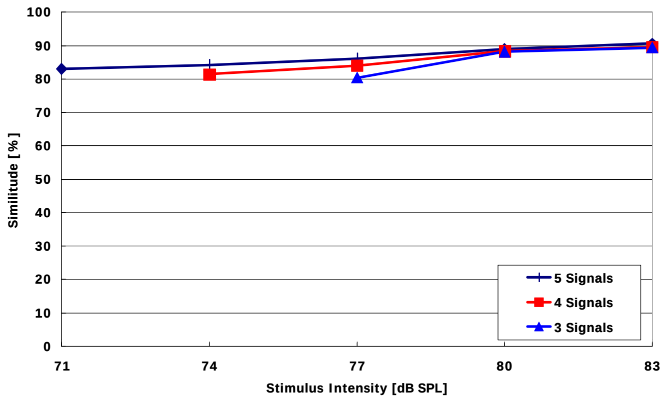

Fig. 3. *Similitude* as a function of the stimulus intensity of the rapidly-acquired set of responses averaged over 60 sweeps with respect to the GS set changing the number of TEOAE responses in the set. The figures are relative to the average over all ears.

IV. Discussion and Conclusion

The reduction of the acquisition time of TEAOE is crucial for the use of otoacoustic emission both in clinical practice and as tool for newborn hearing screening programs (see, e.g., [7]).

This paper presents an innovative method to collect a set of otoacoustic responses with a substantial reduction in acquisition time. The method is based on compiling a rapidly acquired set of responses (averaged over a number of sweeps lower than the classical 260, typical in clinical practice) and applying a PCA approach in order to increase the SNR. As an example, one can record in about the same acquisition time either one otoacoustic response classically recorded averaging 260 sweeps or four responses at different stimulus intensity levels averaged over only 60 sweeps.

To provide a benchmark of the PCA approach performances, *Similitude* was introduced. The comparison between these metrics estimated in all 15 ensembles of recordings before and after PCA processing, with respect to the Golden Standard provided evidence that the use of PCA produces no loss of information in the set of data and that the comparison between the waveforms of the PCA processed and those of the GS confirmed that signal morphology and latency were fairly well preserved.

However, the effectiveness of this procedure strongly depends on the SNR of the original rapidly acquired set of data. Averaging only 10 sweeps usually yielded a very low SNR (Fig. 2), with no appreciable increase in *Similitude* after PCA processing. Therefore, it is advisable to apply the described approach only to set of data with sufficiently high SNR, which for the type of signals addressed by this study is typically achieved with an average of at least 60 sweeps.

Finally, the results of this study suggest that the rapid-acquisition of only three responses at high stimulus levels could be sufficient to obtain satisfactory performances from the PCA approach. In that sense, the PCA approach allows the collection of three responses at different stimulus levels in less than the time of the classical "single shot" (i.e., only one response at stimulus level of 80 dB SPL), used in typical TEOAE-based newborn hearing screening program.

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